EXTRACTING THE FINGERING AND THE PLUCKING POINTS ON A GUITAR STRING FROM A RECORDING

Caroline Traube

McGill University
Department of Electrical
and Computer Engineering
3480 University Street, Rm.633
Montreal, Quebec, Canada H3A-2A7
traube@tsp.ece.mcgill.ca

Julius O. Smith III

Stanford University
CCRMA
Department of Music
Stanford, CA 94305-8180
jos@ccrma.stanford.edu

ABSTRACT

This paper presents a signal processing technique for extracting the plucking point on a guitar string from an acoustically recorded signal. It also includes an original method for detecting the fingering point, based on the plucking point information.

1. INTRODUCTION

Recent years have seen great advances in physical model-based synthesis. In these endeavors, knowledge of the physics and acoustics of the instruments is a theoretical starting point for the modeling. Certain simplifications can make the models computationally efficient and they can then be implemented to run in real-time on a computer. Since implemented physical models are derived from the physics of the instruments, they result in the synthesis of particularly realistic instrumental sounds. But if the physical model running on a computer is intended to be *played*, then research must be extended to the performer's action in order to understand how to interact with the computer model.

For the particular case of the classical guitar, efficient string synthesis algorithms exist and are continually being improved [1, 2, 3, 4, 5]. For the analysis counterpart, research has been undertaken in an attempt to understand the relationships between timbre nuances and model [6], physical, expressive [7, 8] and psychoacoustical [9] parameters.

Among the parameters that contribute to the sound, the plucking point position on the string has a major influence on the timbre nuance. The left hand fingering is crucial too. On the guitar, there are different ways to finger chords or play melodies. A particular fingering will be chosen because it is optimal, efficient and easy to hold, or because it sounds a particular and desired way. Some tones on a guitar can be played with up to five different combinations of string/fret. Thus, if a recording is the only information available, the fingering that was used by a particular performer is not always obvious or apparent.

Hence, the motivations of this research are:

1. to gain a better understanding of the influence of plucking techniques on the timbre of a guitar sound, with a subsidiary goal of improving control of physical models, and
2. to contribute to solving the problem of automatic score and tablature generation, that is to show on the music sheet not only what notes are played but, specifically, which strings are used and how or where they were plucked.

In this paper, a frequency-domain technique for estimating the plucking point is presented and evaluated. This paper also shows that the plucking point information can be used in order to detect the fingering on the left-hand.

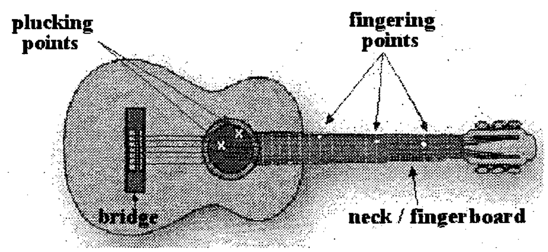

Figure 1: *Location of typical plucking and fingering points on a guitar.*

2. PERCEPTUAL EFFECT OF THE PLUCKING POINT POSITION

Plucking a string close to the bridge produces a tone that is softer in volume, brighter and sharper. The sound is richer in high-frequency components. This happens when playing the guitar *sul ponticello*. The other extreme is playing *sul tasto*, near or over the fingerboard, closer to the midpoint of the string. In that case, the tone is louder, mellower, less rich in high frequency components. The neutral position of the right hand is just behind the sound hole. Because of the position of the right-hand fingers, the low strings are usually plucked further away from the bridge than the higher ones.

3. THEORETICAL CONSIDERATIONS

3.1. Plucking an ideal string

The plucking excitation initiates wave components traveling independently in opposite directions. The resultant motion consists of two bends, one moving clockwise and the other counterclockwise around a parallelogram. In the ideal cases, the output from the string (force at the bridge) lacks those harmonics that have a node at the plucking point. Figure 2 illustrates a plucking position at

1/5th of the length from one end. Note that the spectrum lacks the harmonics that are multiples of 5.

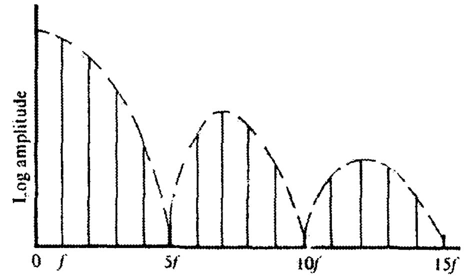

Figure 2: *Spectrum of string plucked one-fifth of the distance from one end [10].*

The general solution of a vibrating string of length l with fixed ends can be written as the sum of normal modes [10]:

$$y = \sum_n (A_n \sin \omega_n t + B_n \cos \omega_n t) \sin(k_n x) \tag{1}$$

where

$$A_n = \frac{2}{\omega_n l} \int_0^l \dot{y}(x, 0) \sin\left(\frac{n\pi x}{l}\right) dx, \tag{2}$$

and

$$B_n = \frac{2}{l} \int_0^l y(x, 0) \sin\left(\frac{n\pi x}{l}\right) dx. \tag{3}$$

So, the amplitude of the nth mode is

$$C_n = \sqrt{A_n^2 + B_n^2}. \tag{4}$$

An ideal plucking excitation at a distance p from an end and with an amplitude h is such that all points along the string have a zero initial velocity:

$$\dot{y}(x, 0) = 0 \qquad \text{for all x,} \tag{5}$$

and the string is initially shaped like a triangle with its summit at the point (p, h):

$$y(x, 0) = \frac{h}{p} x \qquad \text{for } 0 \leq x \leq p \tag{6}$$

$$= \frac{h(l - x)}{l - p} \qquad \text{for } p \leq x \leq l. \tag{7}$$

Therefore,

$$C_n = B_n. \tag{8}$$

Solving the integral, it can be found that

$$C_n = \frac{2h}{n^2 \pi^2 R(1 - R)} \sin(n\pi R), \tag{9}$$

where

$$R = p/l \tag{10}$$

is the fraction of the string length from the point where the string was plucked to the bridge.

3.2. Plucking a real string

A real plucking differs from an ideal plucking in the following ways. The finger or plectrum exciting the string has a non-zero touching width, which adds more lowpass filtering to the excitation. A real excitation is not an event that can be modeled with linear and time-invariant operations. In fact, the finger may grab the string for a short time, while causing nonlinear or linear, but time-varying interactions. Also, the modes of the string vibration are in general nonlinearly coupled so that a mode with zero initial energy will begin to vibrate, gaining energy from other modes [11]. Finally, in the case of an acoustic guitar, the resonating body of the instrument filters the output wave of the string, according to the modes that have been excited (which depend on the plucking angle and plucking style). The forces parallel and perpendicular to the bridge excite different linear combinations of resonances, resulting in tones that have different decay rates [10].

4. ESTIMATING THE PLUCKING AND FINGERING POINT POSITIONS

In general the string is not plucked exactly at the node of any of the lowest harmonics. Since the amplitudes of the higher harmonics is considerably smaller anyway, it is not always possible to accurately detect the plucking point by simply searching for the missing harmonics in the magnitude spectrum.

The method that we investigate here for estimating the plucking point, compares the magnitude spectrum of a portion of the recorded tone to the ideal string spectra calculated for various plucking position values. The plucking point position corresponding to the closest ideal string spectrum is identified. Then the plucking point information is used to estimate the fingering point.

The different stages of the whole procedure are illustrated by the block-diagram in Figure 3.

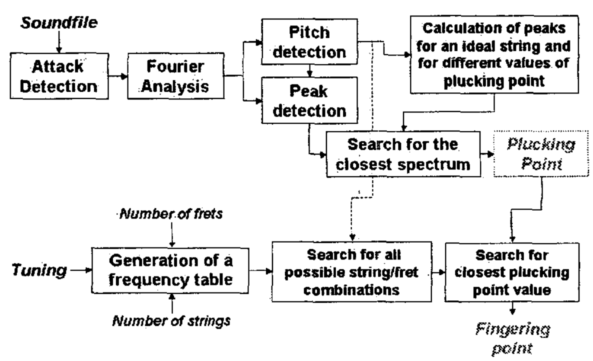

Figure 3: *Block-diagram for the estimation of the plucking and fingering points.*

4.1. Determination of the plucking point

The plucking point is determined from the data by finding the value of R that minimizes the absolute value of the error between the ideal string magnitude spectrum and the sampled-data spectrum, as shown in equation 11,

$$\epsilon = \sum_{n=1}^{N} \left| p_n - \left| \frac{2h}{n^2\pi^2 R(1-R)} \sin(n\pi R) \right| \right| \quad (11)$$

where p_n is the amplitude of the nth harmonic in the magnitude spectrum of the recorded tone excerpt and N is the number of harmonics taken into account for the comparison between ideal and real spectra.

An error curve is constructed by evaluating the error criterion for various values of R. The plucking point should correspond to minimum error. A similar method was described in [12], although their equation for C_n contained a flaw that we correct here in equation 9.

4.2. Determination of the fingering point

4.2.1. Ambiguity of the guitar fingering

Figure 4 illustrates the ambiguity of the fingering on a guitar. The plucking points are represented by $\times$'s and the fingering points by o's. The bridge is the termination on the left and the nut on the right. With a standard tuning EADGBE, the same pitch would be produced in the three cases of fingering shown in Figure 4, since the finger is shifted by 5 frets (corresponding to an interval of one perfect fourth) towards the nut, from the E- to the A- and the A- to the D-string. The *absolute* plucking point is the same but the *relative* plucking point is dramatically different. In fact, we have to consider the new length of the string, from the bridge to the left-hand finger pressing the string against the fret.

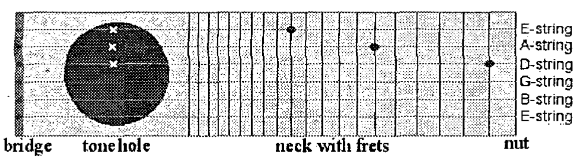

Figure 4: *Simplified representation of the neck of a guitar with plucking points ($\times$) and fingering points (o). The three string/fret combinations produce the same pitch (in this case, D-sharp).*

If we assume that the right-hand fingers pluck the strings in a narrow area close to the tone hole, the plucking point information can help to determine where the strings were fingered, by eliminating the above-mentioned ambiguity.

4.2.2. Generation of a frequency table

Given the tuning, the number of strings and the number of frets, a table of fundamental frequencies corresponding to all the string/fret intersections is generated. For a given string, the frequency is the tuning frequency if the string is open (fret 0). Since going a semitone up corresponds to a factor $2^{1/12}$, the other frequencies are obtained by multiplying the tuning frequency by $2^{F/12}$, where F is the fret index.

4.2.3. Search for closest plucking point value and determination of the fingering

By subtracting the detected fundamental frequency of the tone from the frequency table and taking the absolute value of the elements of the resulting matrix, a table of distances is obtained. The possible string/fret combinations are determined by searching for distances smaller than a quarter of a tone,

For each string/fret combination determined at the previous stage, an approximate plucking point is calculated, assuming that the plucking is performed near the tone hole, which is at about one fourth of the strings' length.

Considering that the length of the vibrating portion of a string is shortened by a factor $2^{-1/12}$ for each semitone, the approximate relative plucking point distances can be calculated for all possible string/fret combinations.

The relative plucking distance that is the closest to the value estimated previously should correspond to the fret/string combination that is the most likely.

Finally, knowing the fingering position and therefore the length of the vibrating portion of the string and knowing the relative plucking point position, the absolute plucking point distance from the bridge can be determined.

5. TESTING AND RESULTS

5.1. Sound database

In order to test the algorithms, a database of recorded tones was created. Three different guitars were used: a hand-made 1995 Collings acoustic guitar strung with John Pearce phosphor bronze medium gauge strings, a plywood classical guitar strung with nylon and nylon-wrapped steel Alvarez strings, and a 1953 Martin 000-18 acoustic guitar strung with John Pearce phosphor bronze light gauge strings.

The tones were played with a plastic pick, .88 millimeters in thickness, triangularly shaped. The intended plucking points were precisely measured and indicated on the string with a marker. The tones were recorded with a Shure KSM32 microphone in a sound-deadened room, onto digital audio tape (DAT) at 44.1 kHz, 16 bits. The microphone was placed in front of the sound hole, approximately 6 inches away, which was far enough to capture a combination of waves coming from different parts of the string, in that way limiting the filtering effect due to the microphone location.

Different series of plucks were recorded: plucks at special points along the string (1/2, 1/3, 1/4), plucks at every centimeter from the bridge to the middle of the string on open strings, chromatic scales with plucking point distance from the bridge kept constant and three-tone melodies fingered in different ways.

5.2. Results for plucking point estimation on open strings

Figure 5 displays the results for three distances from the bridge (12, 13 and 14 cm).

The presentation of the results is as follows:

- left window: Fourier analysis of a 4096-sample portion of the sound with peak detection indicated by circles.
- middle window: error curves for various values of plucking distances D ranging from 1 to 20 cm. The minimum is indicated by a circle and the corresponding D value is displayed. The resolution of D is 0.1 cm.
- right window: comparative display of the detected peaks (o) and of the ideal string magnitude spectrum ($*$) based on the intended pluck position.

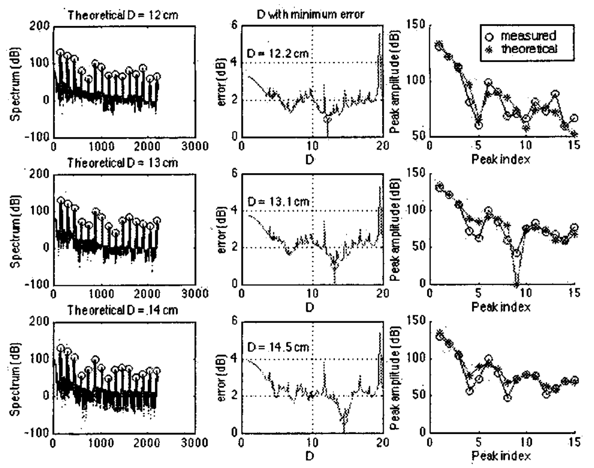

Figure 5: *Plucking point distance from the bridge D = 12, 13, 14 cm. Tones played on the classical guitar.*

This last display was crucial in figuring out a problem of amplitude mismatch. The measured and ideal spectra have to be matched in amplitude otherwise the computation of the error does not make sense. The code includes an autonormalization with alignment on the second harmonic. In fact, the first harmonic of the comb filter is always the highest peak, but this is not always the case for the real data spectra.

Figure 6 summarizes the results obtained for the 18 plucking points on the open A-string and open D-string. The graph displays the estimated distance versus the measured distance on the string when the tone was played. The accuracy is better than one centimeter.

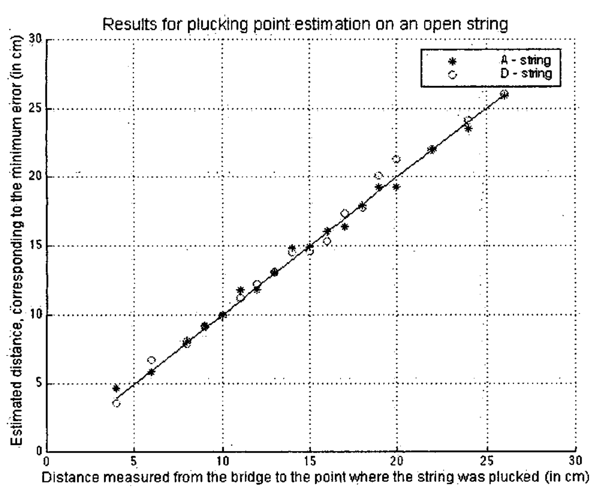

Figure 6: *Plot summarizing the results for 18 plucks on open D- and A-strings of the classical guitar.*

6. CONCLUSION

We presented an attempt to solve the problem of estimating the plucking point on a guitar string from an acoustically recorded signal.

The implemented technique for estimating the plucking point gives very good results for recordings of tones played on unfretted strings. The results for fretted strings are not as good, but more testing would probably help to determine the cause and a way to compensate for it.

The original method proposed for estimating the fingering point is efficient in all its stages (attack, pitch and peak detection, determination of possible fret/string intersections) but its accuracy depends on the performance of the plucking point estimation.

7. REFERENCES

[1] Jaffe, D.A., and Smith, J.O., "Extensions of the Karplus-Strong Plucked-String Algorithm", Computer Music Journal, Vol. 7, No. 2, pp. 56-69, Summer 1983.

[2] Karjalainen, M., Valimaki, V. and Janosy, Z., "Towards High-Quality Sound Synthesis of the Guitar and String Instruments", Proc. International Computer Music Conference, pp. 56-63, 1993.

[3] Smith, J.O., "Efficient Synthesis of Stringed Musical Instruments", Proc. International Computer Music Conference, pp. 64-71, 1993.

[4] Valimaki, V., Huopaniemi, J., Karjalainen, M. and Janosy, Z., "Physical Modeling of Plucked String Instruments with Application to Real-Time Sound Synthesis", J. Audio Engineering Soc., Vol. 44, No. 5, pp. 331-353, May 1996.

[5] Karjalainen, M., Valimaki, V. and Tolonen, T., "Plucked-String Models: From the Karplus-Strong Algorithm to Digital Waveguides and Beyond", Computer Music Journal, 22:3, pp.17-32, Fall 1998.

[6] Tolonen, T. and Valimaki, V., "Automated Parameter Extraction for Plucked String Synthesis", Proc. International Symposium on Musical Acoustics, vol. 1, pp. 245-250, Scotland, 1997.

[7] Erkut, C., Valimaki, V., Karjalainen, M. and Laurson, M., "Extraction of Physical And Expressive Parameters for Model-based Sound Synthesis of The Classical Guitar", AES108th Convention, Paris, 2000

[8] Cuzzucoli, G. and Lombardo, V., "A physical Model of the Classical Guitar, Including the Player's Touch", Computer Music Journal, 23:2, pp. 52-69, Summer 1999.

[9] Orio, N., "The timbre space of the classical guitar and its relationship with the plucking techniques", Proc. International Computer Music Conference (ICMC'99), pp.391-394, China, 1999.

[10] Fletcher, N.H. and Rossing, T.D., The Physics of Musical Instruments, second edition, Springer-Verlag, 1998.

[11] Legge, K.A., and Fletcher, N.H., "Nonlinear generation of missing modes on a vibrating string", J. Acoust. Soc. Amer., Vol. 76(1), 1984.

[12] Bradley, K., Cheng, M.-H. and Stonick, V.L., "Automated Analysis and Computationally Efficient Synthesis of Acoustic Guitar Strings and Body", Proc. IEEE ASSP, 1995.